Weak Lensing Program

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Outline

1. Weak Lensing – Brief Overview
2. Implications for Mission Design
3. Final Thoughts

1. Weak Lensing – Brief Overview

What is Weak Lensing?

- Slight (~1%) distortion of the image of a galaxy due to matter along the line of sight.
  - Shear = l.o.s. integral of tidal field
    - Manifest in the ellipticity of a galaxy.
    - Since shear << intrinsic ellipticity, must do statistics.

  - Magnification = l.o.s. integral of density
    - Less mature but lots of recent progress – only briefly in this talk.

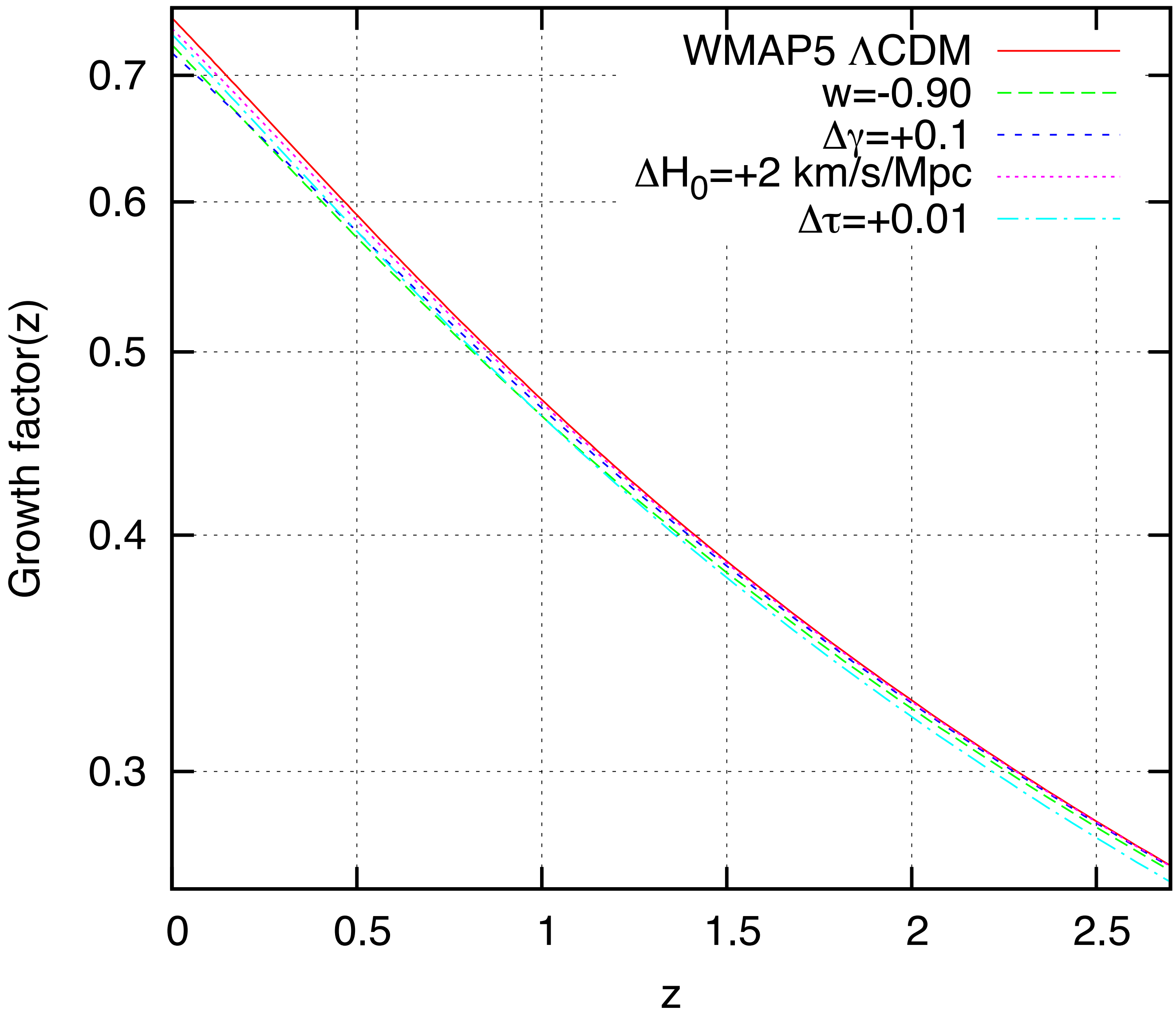
Thanks to B. Jain for the cartoon.

Major Uses

WL serves both cosmology and galaxy evolution

1. The growth of large scale structure via the statistics of weak lensing.
2. The connection between galaxies and their host dark matter haloes.
3. Galaxy "biasing" – the relation between galaxies and their large-scale environment.

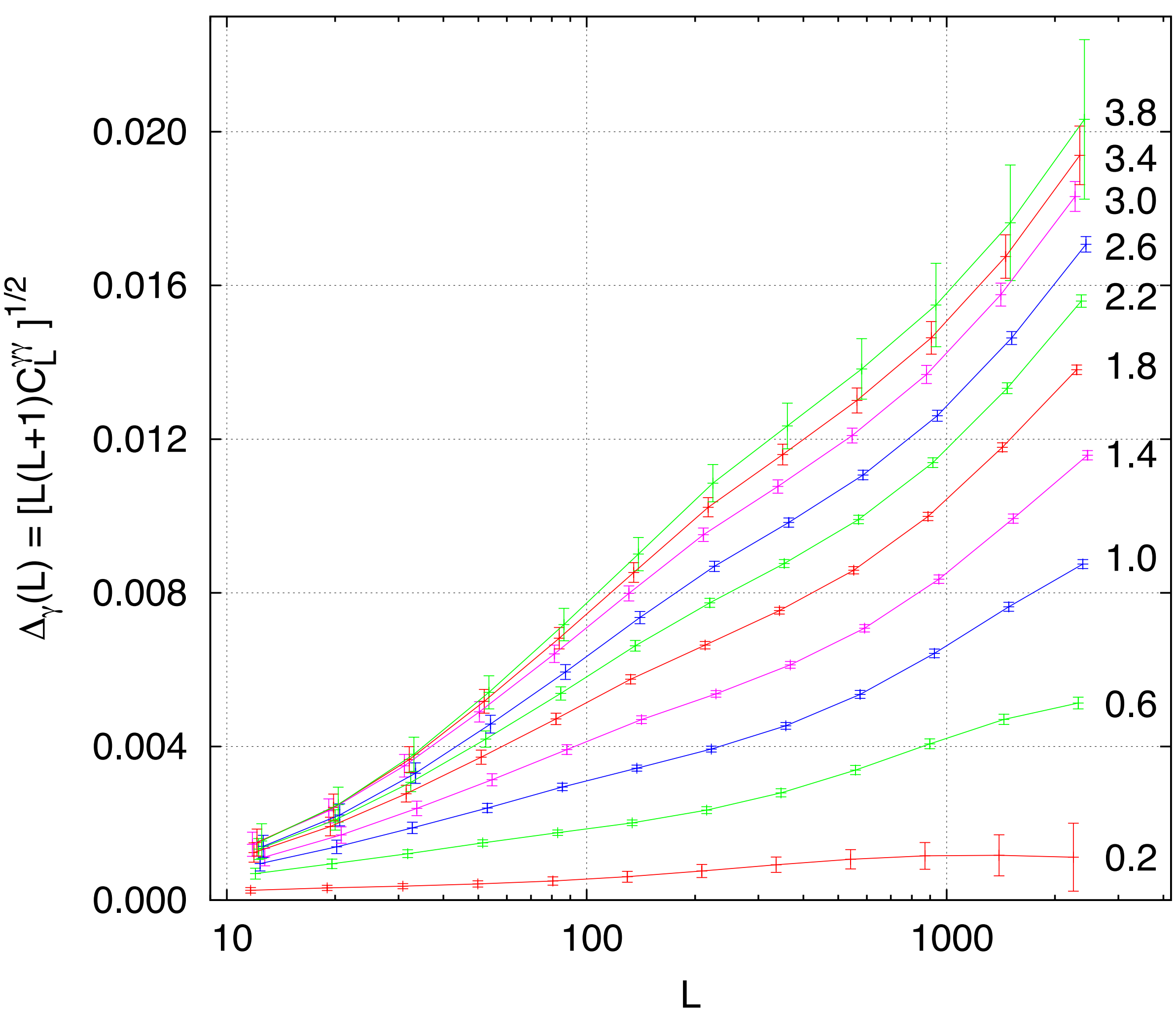
Growth factor for linear matter perturbations



- Fixed high-z universe to keep same CMB normalization
- w = dark energy equation of state (=−1 for cosmological constant)
- γ = growth rate parameter (≈0.6 in GR)

$$f \equiv \frac{d \ln G}{d \ln a} = \Omega_m^{0.6}$$

Observable: the shear power spectrum



- Shear power spectrum as a function of source redshift z_s
- This is actually an integral over structures at $0<z<z_s$; depends on distance scale as well as structure growth.
- Error bars are DRM1 forecasts.
- Much more information in the 45 cross-power spectra.
- Depends on almost every conceivable cosmological parameter. Combine with other datasets to break degeneracies.

SDSS Results

[i.e. shamelessly promoting our own work]

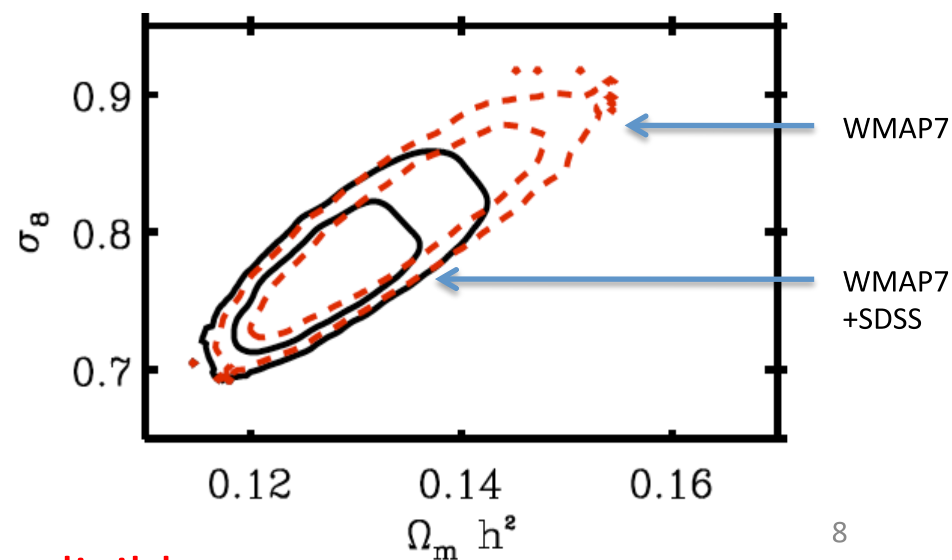
- Amplitude of fluctuations (Huff et al):
  - Fixed other parameters to WMAP values

$$\sigma_8 = 0.64^{+0.10}_{-0.15}(1\sigma)$$

- Independent analysis of the same dataset by Fermilab group (Lin et al):
  - Includes e.g. different image stacking algorithm, sky subtraction, etc.

$$\sigma_8 = 0.64^{+0.08}_{-0.13}(1\sigma)$$

- This worked but:
  - Statistical errors are large
    - ~ 10 results in the literature of similar size errors; 1/√10 game not recommended
  - Limited redshift baseline
  - Systematic errors small but not negligible



What is needed for a WL program?

- Statistics
  - Lots and lots of galaxies
- Shape Measurement
  - Resolve and fully sample galaxies, high S/N
  - Accurate knowledge/correction of PSF + detector effects
  - Power/cross spectra from multiple redundant subsets of the data (for cross checks internal to WL method).
- Photometric Redshifts
  - Required both to measure signal(z) and suppress intrinsic alignments (needs low outlier fraction)
  - Photometric data points from (at least) *u*—H bands.
  - Calibration sample (with massively multiplexed spectrographs).

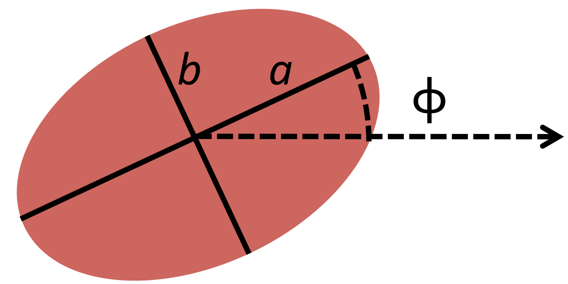
- ***There may be some substitutability on these points (e.g. outside OIR bands), and some fractions of the program are possible with subsets of the data. However we can't skimp on a requirement just because it's hard.***
- ***There is no requirement to do all of this from the same platform. No one of LSST, WFIRST, or Euclid is a complete program by itself!***

Shape measurement conventions

[See Bernstein & Jarvis 2002 for the 40-page version of this slide]

Ellipticity: A property of the *galaxy* – may be:

- Intrinsic or observed (i.e. including lensing)
- With or without PSF smearing
- Depends on fitting method for general galaxy



$$e_1 = \frac{a^2 - b^2}{a^2 + b^2}\cos 2\phi \qquad e_2 = \frac{a^2 - b^2}{a^2 + b^2}\sin 2\phi$$

Shear: A property of the lens mapping

$$\frac{\partial x_{\mathrm{source}}}{\partial x_{\mathrm{image}}} = \begin{pmatrix} 1-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1+\gamma_1 \end{pmatrix}$$

Responsivity: Relation of mean ellipticity of galaxy population to shear (depends on the galaxy population and ellipticity measurement method)

$$\langle e_i \rangle = 2\Re \gamma_i$$

Resolution factor: Intrinsic size of the galaxy relative to the PSF (Between 0 and 1, bigger is better)

$$R = \frac{r_{\mathrm{eff,gal}}^2}{r_{\mathrm{eff,gal}}^2 + r_{\mathrm{eff,psf}}^2}$$

The WFIRST weak lensing program has the raw statistical power to measure σ_8 to ±0.001. Similar advances will be made on the other parameters relative to current weak lensing programs.

But we are trying to measure a 1% shear signal to 0.1% accuracy. Reliable results at this level will require ~2 order of magnitude improvement in systematic error control in shape measurements. Other big WL programs (LSST, Euclid) face similar issues.

Improvements also needed in other areas, e.g. photo-z training → but that's another talk (ask me later about Subaru-Prime Focus Spectrograph)

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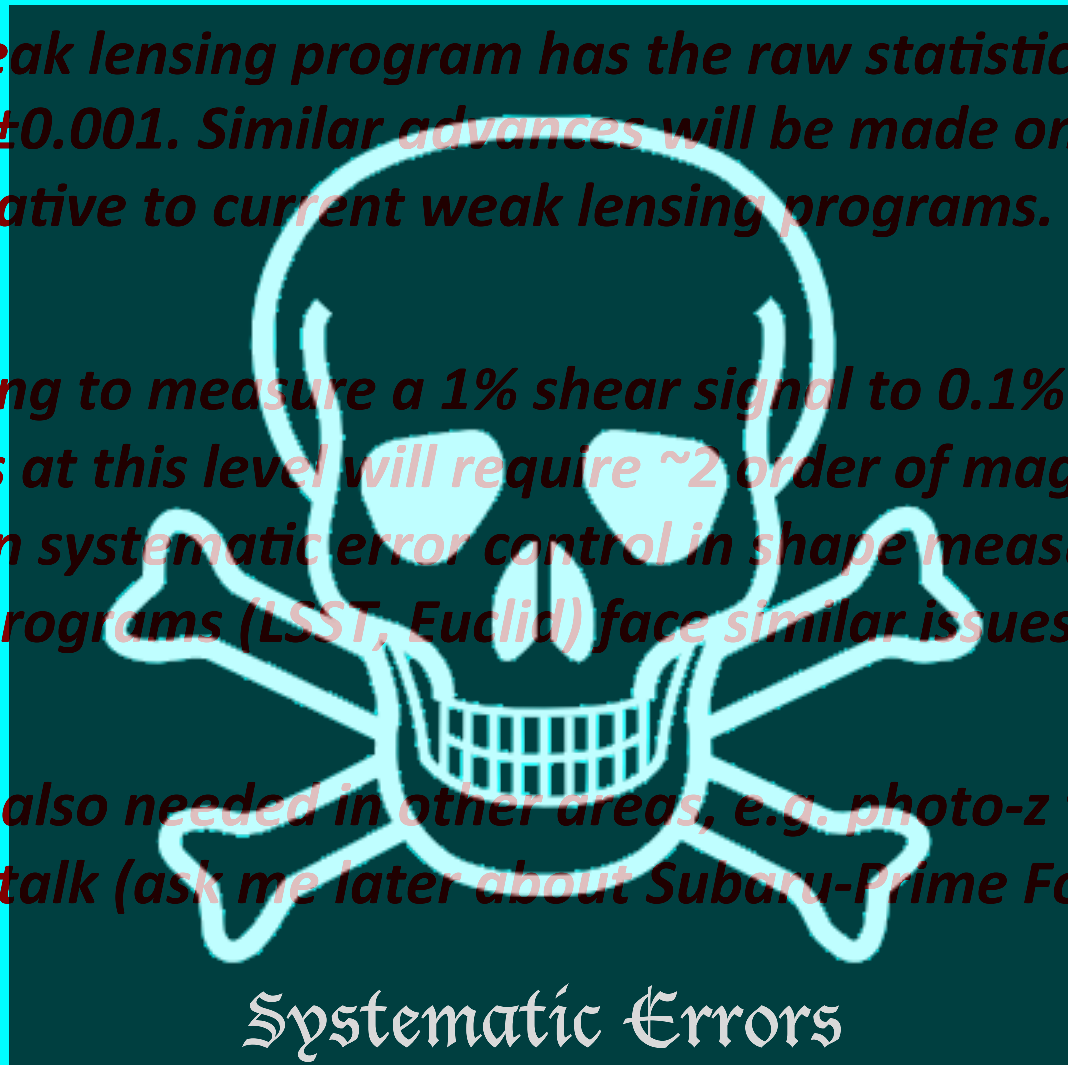
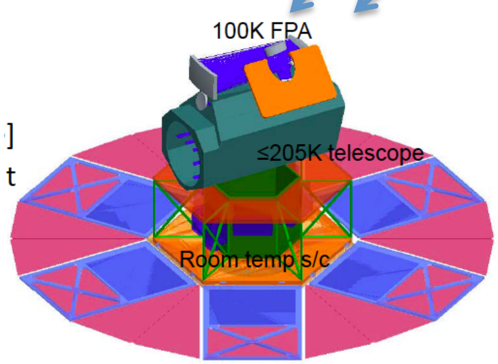


The Major Systematic Errors

Intervening matter:
- Nonlinear power spectrum/
  multiple deflections?
- Baryonic corrections?

Source galaxies:
- Redshifts?
- Intrinsic alignments?

Telescope/instrument:
- Point spread function?
- Flats, astrometry … ?
- Detector linearity?



Data analysis:
- Image processing algorithms?
- Source selection/blending?
- Shape measurement?

2. Implications for Mission Design

Contents:
Galaxy yields & statistical errors
Sampling
PSFs
Systematic errors

Advantages of WFIRST Architecture

1. Observations at L2? with a temperature-controlled telescope eliminate both the atmosphere and the large thermal fluctuations experienced on the ground and on HST.

2. Fully-sampled images in 3? shape measurement filters (JHK?) enable internal cross checks and color corrections on every galaxy.

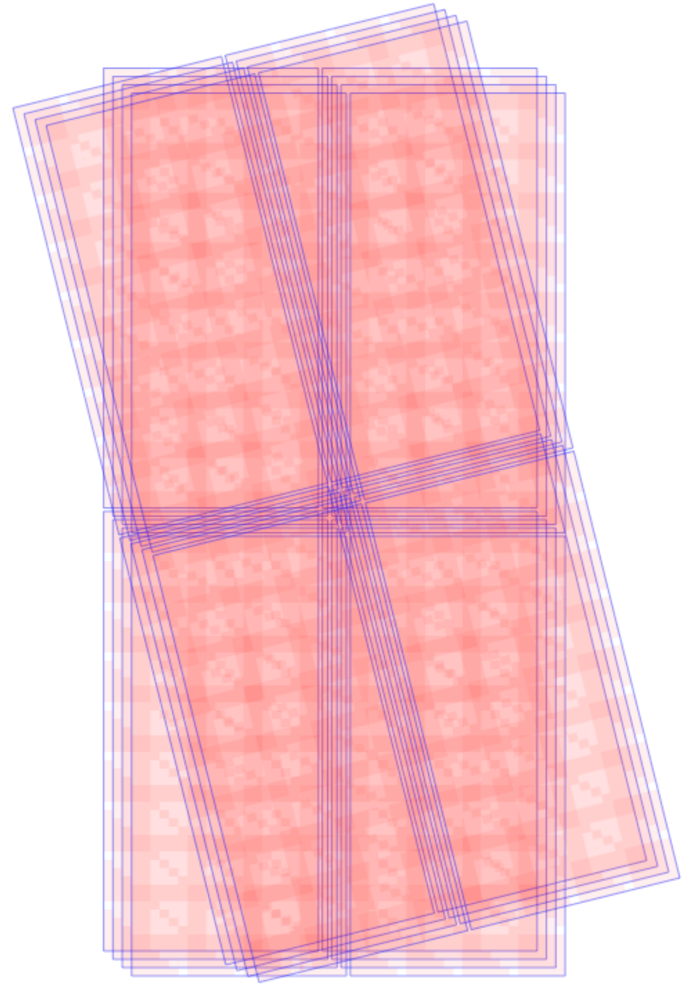
3. Redundant passes in each filter support calibration and null tests internal to the science data itself.

4. ~~Unobstructed~~ big telescope allows ~~simple, compact~~ small PSF even in the NIR, where galaxies are bright.

5. High-SNR photometry in YJHK?, obtained simultaneously with shape measurement and combined with ground based data, allow for unambiguous photo-z's across the entire relevant range of redshifts.

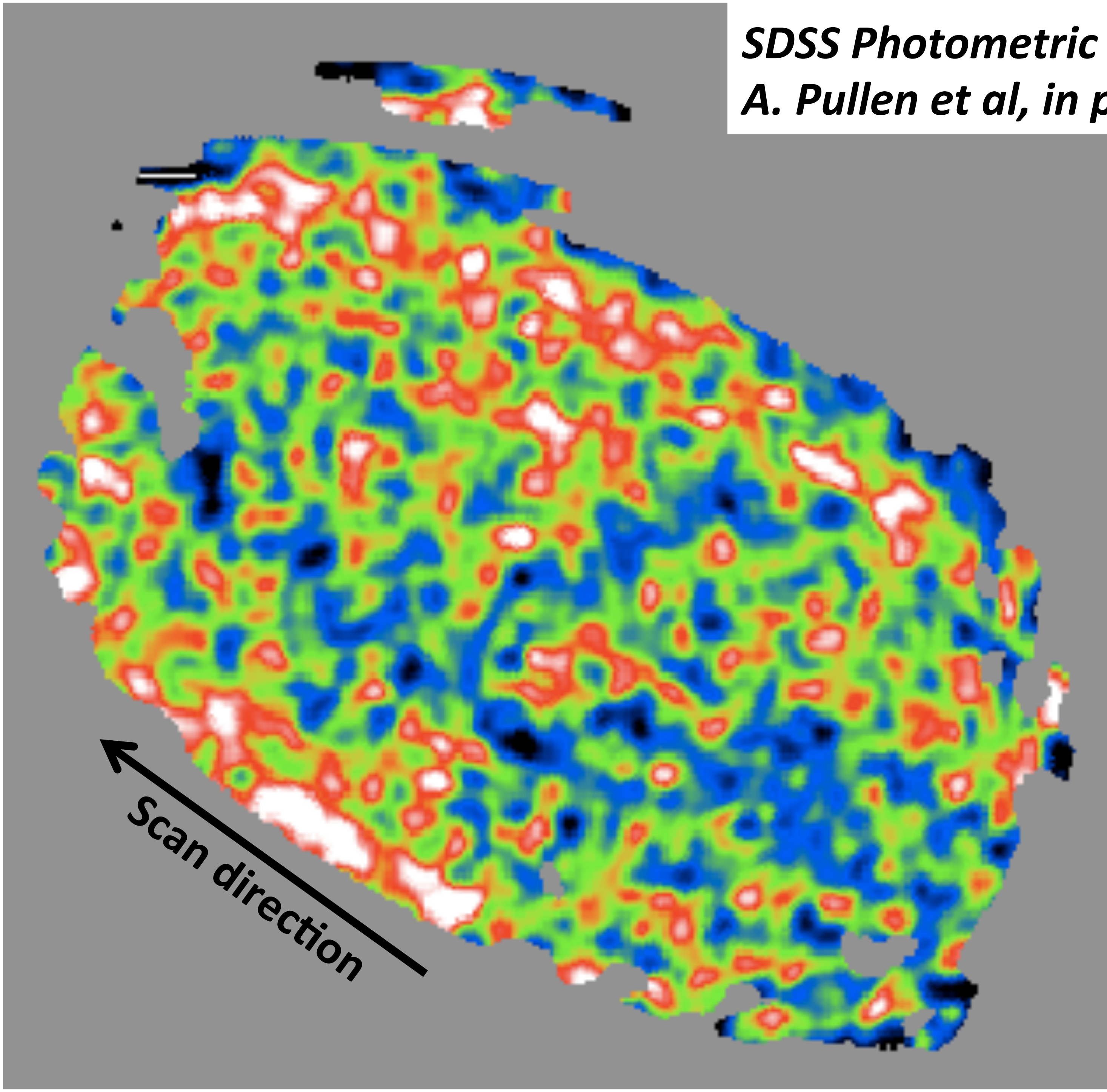
Some comments on tiling

- WFIRST operations concept includes multiple passes over the sky, separated in time, and rolled.
  - Allows internal relative calibration, field dependence of color terms, any contributions to the PSF fixed to the detector … at relevant background levels.
  - Null tests available at the image processing level.
  - Also enables other precision applications, e.g. f_{NL} studies …
- Covering the sky in stripes is faster, but won't allow these tests. Don't give in to the temptation!



DRM1 strategy
(DRM2, AFTA similar)

SDSS Photometric Quasar Density
A. Pullen et al, in prep



Galaxy populations

- Forecasts generally based on some input catalog and a model for which galaxies will lead to measurable shapes.
  - Inputs for forecast based on COSMOS. At AFTA depth this may be too conservative due to incompleteness (we're working on this).
- Current WFIRST forecasts (IDRM, DRM1/2, and now this study) assume:
  - Detected at SNR>18 (need this cut to keep noise-related biases small, generally ~$1/SNR^2$ – we will have to trust the correction!)
  - Ellipticity measurement $\sigma_e<0.2$ (density of objects gets downweighted if σ_e comparable to intrinsic spread – this downweighted density is n_{eff})
  - Resolution factor R>0.4
- In principle we could push all of these cuts somewhat farther but must carry margin.

PSF half light radius, r_{eff}

Units are arcsec

	DRM2	DRM1	DRM0
Z	0.174	0.148	0.111
Y	0.181	0.154	0.120
J	0.195	0.166	0.134
H	0.218	0.185	0.150
K [K_s]	0.252	0.214	 [0.165]

Shape measurement filters

DRM0 is 1.5—1.6x better than DRM2, and 1.2—1.3x better than DRM1.

Imaging depths/times at 250 K

	Case A	Case B	Case C
Y	5 x 94 s **25.93**	5 x 131 s **26.39**	5 x 247 s **27.10**
J	6 x 84 s **25.92**	6 x 115 s **26.37**	6 x 205 s **27.02**
H	5 x 94 s **25.95**	5 x 131 s **26.40**	5 x 247 s **27.07**
K_s	5 x 147 s **25.82**	5 x 246 s **26.33**	5 x 247 s **26.33**
Time (days per 1000 deg^2)	**128** [87 without K_s]	**178** [113 without K_s]	**260** [195 without K_s]

- Table shows exposure times and depth (5σ pt src, AB mag)
- DRM2 uses **126** days per 1000 deg^2 (would be 94 days without K filter)
- Assumed a "K_s" filter at 1.83—2.15 μm in place of DRM1/2 K filter.

Weak Lensing Performance

		DRM2	DRM1	AFTA-A (250 K)			AFTA-A (280 K)		
Survey Rate Case				A	B	C	A	B	C
n_{eff} [gal / arcmin^2]	J	24	31	25	34	63	25	34	63
	H	27	33	31	46	70	31	46	62
	K or K_s	24	32	31	46	46	N/A	N/A	N/A
Time [days / 1k deg^2]		**126**	**131**	**128**	**178**	**260**	**88**	**118**	**195**

- All calculations are at the nominal number of exposures.
  - Once we are closer to the final design, we will take credit for the regions observed ≥N+1 times.
  - For consistency, this table shows the equivalent numbers from DRM1/2.
- The time includes the Y band imaging (for photo-z).
- This is still based on the COSMOS catalog. **DRM0 Case C may suffer incompleteness and there will be a modest increase.**
  - This is a somewhat nontrivial exercise to do right – a job for the SDT.

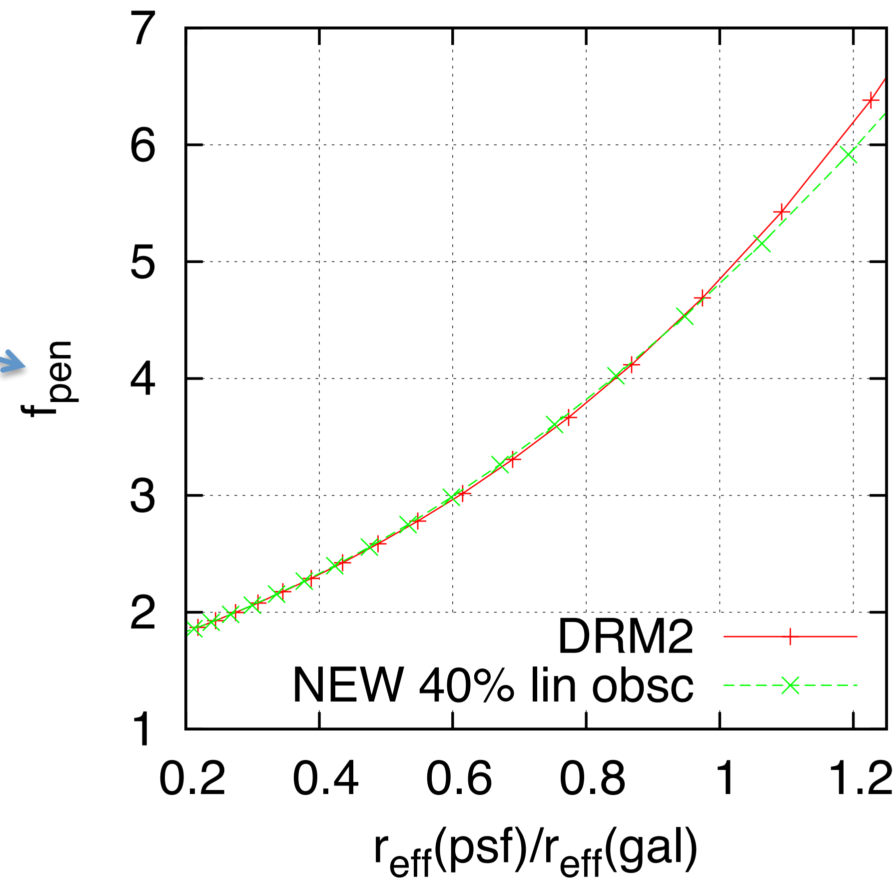
Why are we using the PSF half light radius?

- ✓ WL shape measurement depends on the SNR of a galaxy and a "penalty factor" for PSF smearing and non-Gaussian profile.

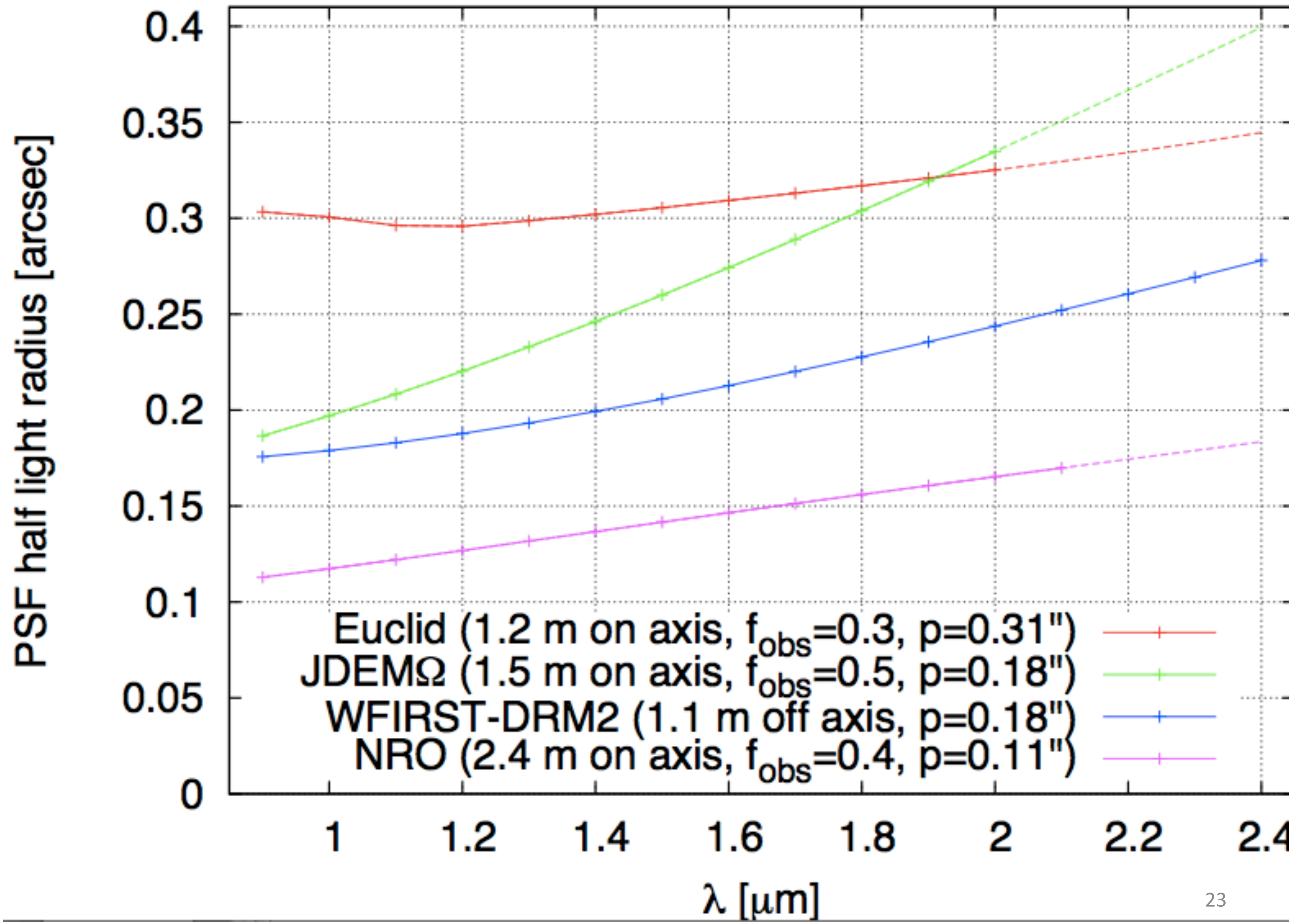
$$\sigma_e = \frac{2\sqrt{f_{\mathrm{pen}}}}{\mathrm{SNR}}$$

- ✓ The plot on the right shows a comparison of WL shape measurement penalty factor for DRM2 and 2.4 m on-axis (computed by the Fisher matrix integral over spatial frequencies), for an exponential profile galaxy in H band.

- ✓ In comparing off- and on-axis telescopes, **scaling by the half-light radius is an excellent indicator of the amount of degradation**.



[Ratio of half-light radii]


PSF half light radius [arcsec]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
λ [μm]
Euclid (1.2 m on axis, f_{obs}=0.3, p=0.31")
JDEMΩ (1.5 m on axis, f_{obs}=0.5, p=0.18")
WFIRST-DRM2 (1.1 m off axis, p=0.18")
NRO (2.4 m on axis, f_{obs}=0.4, p=0.11")

Sampling I

- Images on multipixel detectors are (noisy) discrete samples of a continuous field:

$$I(\mathbf{x}) = [f * G](\mathbf{x})$$

  - f = actual image of the sky
  - G = point-spread function (including detector response)
  - I = observed image
  - * = convolution
- WL data analysis operations work on “continuous” data.
- But real images are discrete since they are observed on pixelized detectors. Only sampled at positions $\mathbf{x} = (j_1 P, j_2 P)$ where P = pixel scale, j_1,j_2 = integers.
- Sampling theorems tell us when discrete data can be transformed into continuous data.

Sampling II

- A function is band limited if its Fourier transform is 0 beyond some maximum frequency *W*:

$$I(x,y) = \int \tilde{I}(u,v) e^{2\pi i(ux+vy)} du dv \quad \Leftrightarrow \quad \tilde{I}(u,v) = \int I(x,y) e^{-2\pi i(ux+vy)} dx dy$$

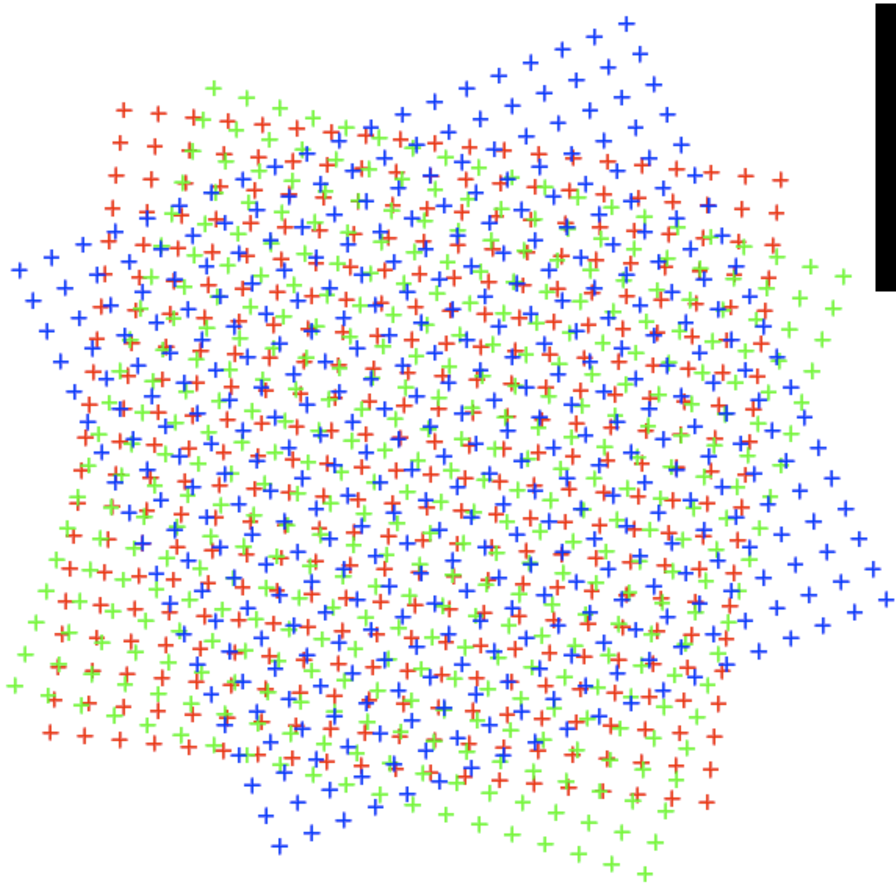
$$\tilde{I}(u,v) = 0 \quad \text{for} \quad \sqrt{u^2+v^2} \geq W$$

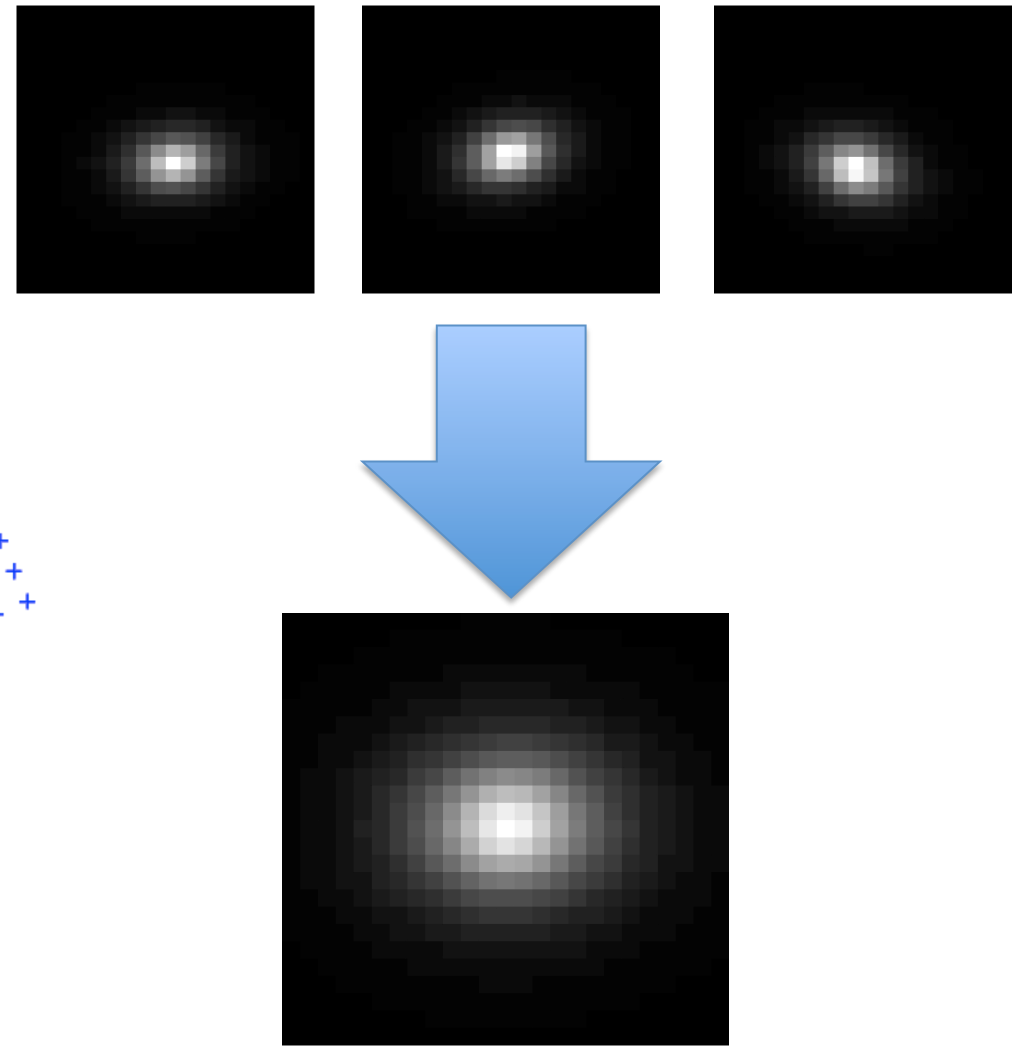
- In this case samples on a regular grid of pitch <1/(2*W*) enables transformation into a continuous function.
  - Rotation, translation, and (with some restrictions) shear and postprocessing changes to the PSF are then simple.
- Only band limit guaranteed by fundamental physics is *D*/λ.
  - Even in the case of obstructions.
  - Other contributions (pixel response, jitter) may occur in some cases.
  - Galaxies have no band limit – required sampling is set by the PSF.

Options for Recovering Full Sampling

1. Full sampling at native pixel scale
   - Common in ground based applications where seeing eliminates high spatial frequencies
   - For diffraction limited space mission this requires pixel scale <$\lambda/(2D)$ – usually too small FoV.
2. Full sampling through ideal subpixel (½ or ⅓) dithers
   - Common in HST programs
   - Positions must be repeated to dodge defects (CRs, hot pixels)
   - Only very small dithers can be accommodated with geometric distortions – not well suited to wide angle filled surveys or internal relative calibration
3. Full sampling through non-ideal/rolled dithers
   - This case naturally occurs in wide angle filled surveys, e.g. WFIRST!
   - Must handle irregularly sampled data, different PSFs
   - No simple, generally applicable theory – handled by simulations (Rowe, Hirata, Rhodes 2011)

An Example

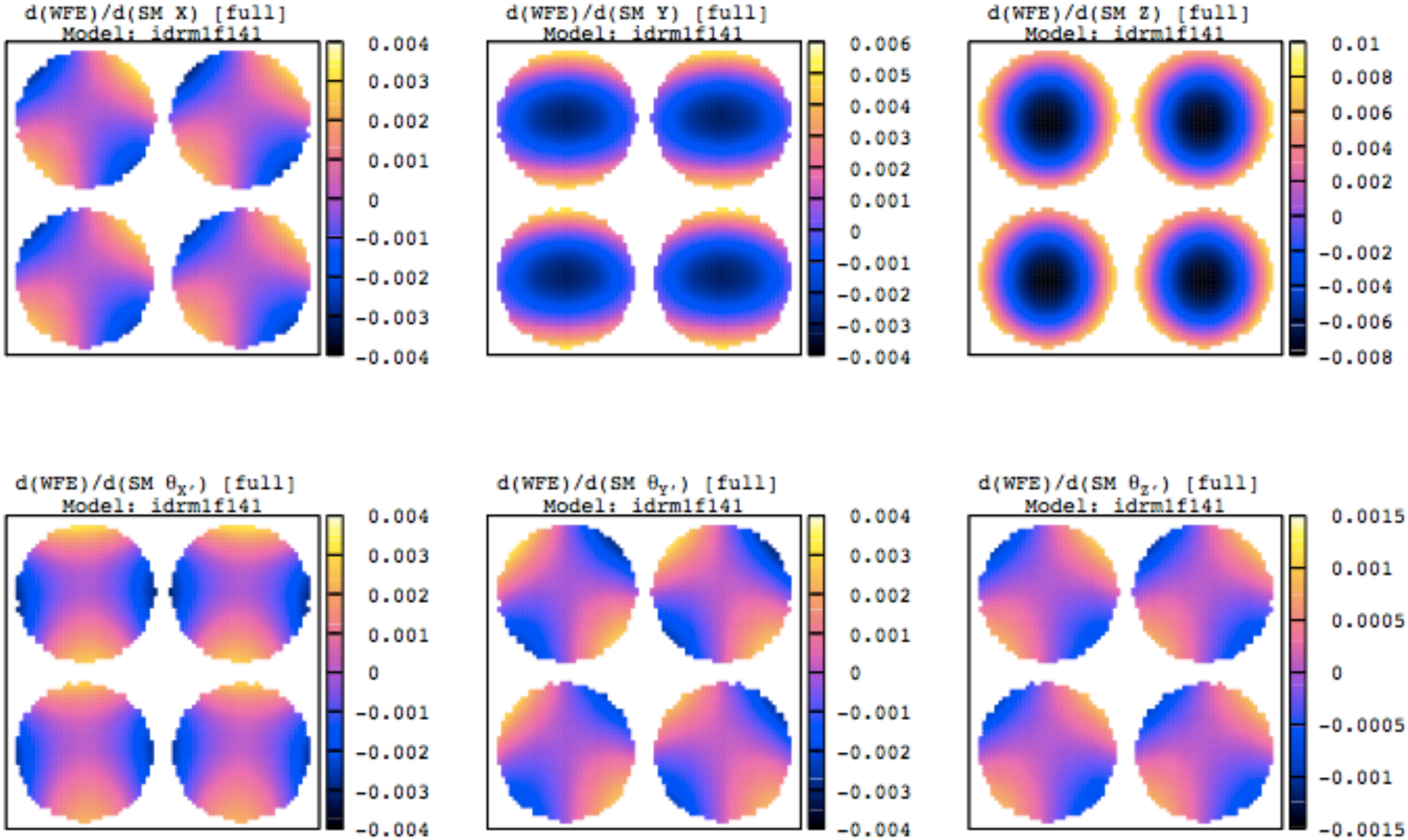




PSFs

- Key advantage in space is a PSF that is small and stable.
- Must measure PSF using stars and track changes (aberrations, jitter)
  - Overall error budget is 4×10^{-4} for in-band PSF errors (scales >1')
    - Note: "in band" means we don't need the PSF to this accuracy in every pixel
    - Applies to final data product so covers additional errors introduced by e.g. stacking
  - Must keep number of varying degrees of freedom finite & small
    - Do not want to allow aberrations to change during an exposure.
  - See IDRM sims by Alden Jurling
- Changes due to e.g. SM motion result in changes in the Zernike amplitudes that are low-order polynomials across the field.
  - But can lead to PSF ellipticity variations at all scales by beating against e.g. focal plane non-flatness.

WFIRST-IDRM Wavefront Distortion Map
(Sensitivity to Secondary Mirror Perturbations)



- *Significant astigmatism from de-centering SM, but varies slowly across field.*
- *Other off-axis concepts, e.g. DRM2, give similar patterns.*
- *In on-axis concepts, dominant aberration from de-centering SM is coma instead.*

PSF Stars

- Determination of PSF from stars scales roughly as 1/sqrt{N_γ}, where N_γ is the total number of photons from stars.
  - If S/N is distributed across the focal plane and not concentrated in a few stars.
  - Getting enough stars has been a problem in WL programs on narrow field telescopes (HST).
- Expected from Trilegal model @ SGP:
  - Only count stars of high S/N (≥10k photons/star) and far from full well (<50k photons in the brightest pixel)

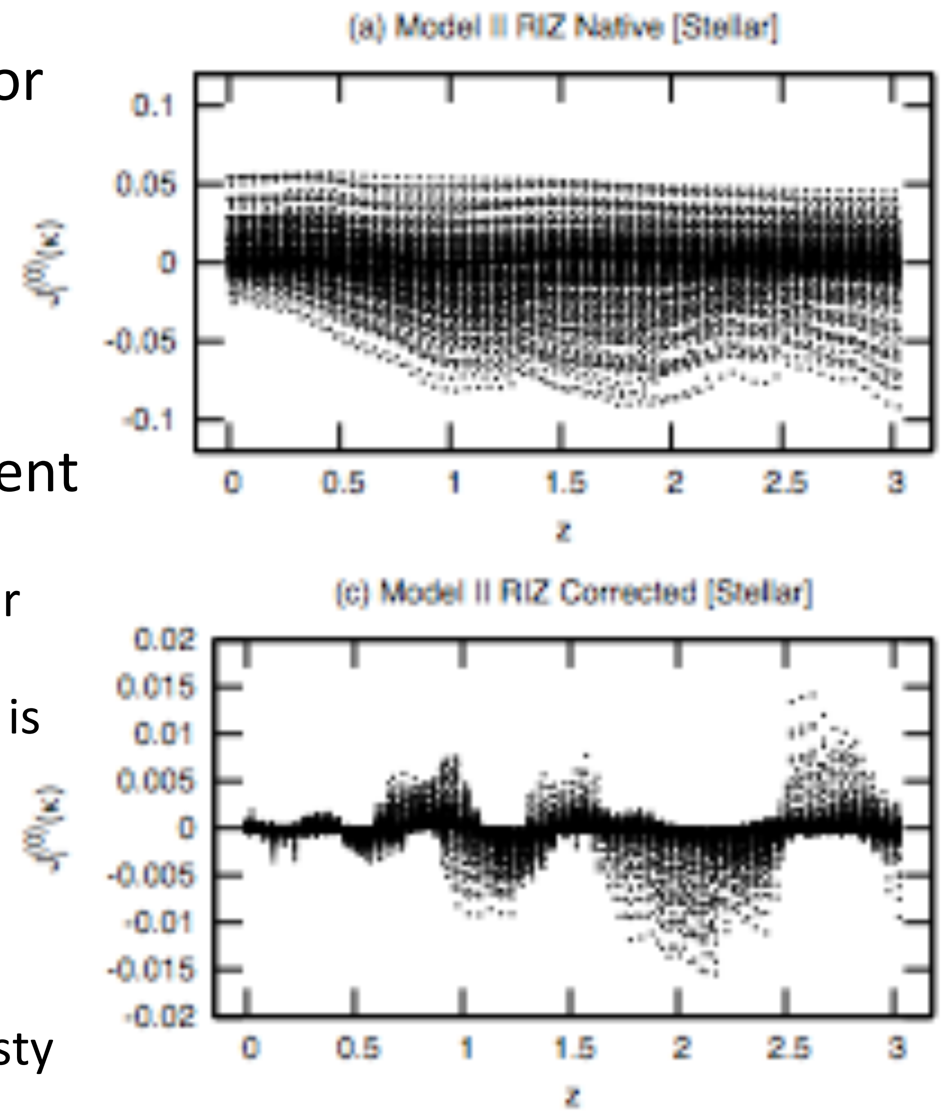
	J		H		K or K_s	
	N_*	N_γ	N_*	N_γ	N_*	N_γ
DRM1	658	31M	708	38M	693	43M
DRM2	1143	64M	1195	74M	1185	89M
DRM0A Case A	540	30M	603	34M	580	39M
DRM0A Case B	610	34M	676	39M	679	45M
DRM0A Case C	696	40M	800	47M	681	46M

Is your PSF the one you want?

- Assumption is that PSF stars must track the same integration time used for the galaxies (to get the same jitter pattern).
  - No saturated stars – even if you have a few samples before saturation.
  - No stars or galaxies with ramps corrected for cosmic ray impacts.
- (Non)-linearity/reciprocity
  - Stars are typically ~300 times brighter than background
  - Need to measure the relevant nonlinearity curve (exposure time, sampling method); several methods possible
- Color effects
  - SED(star) ≠ SED(galaxy), variation even within a galaxy
  - Diffraction/aberrations
  - Refractive optics (lateral color introduced by filter)
  - Depth of charge deposition in detector (what happens to PRF?)

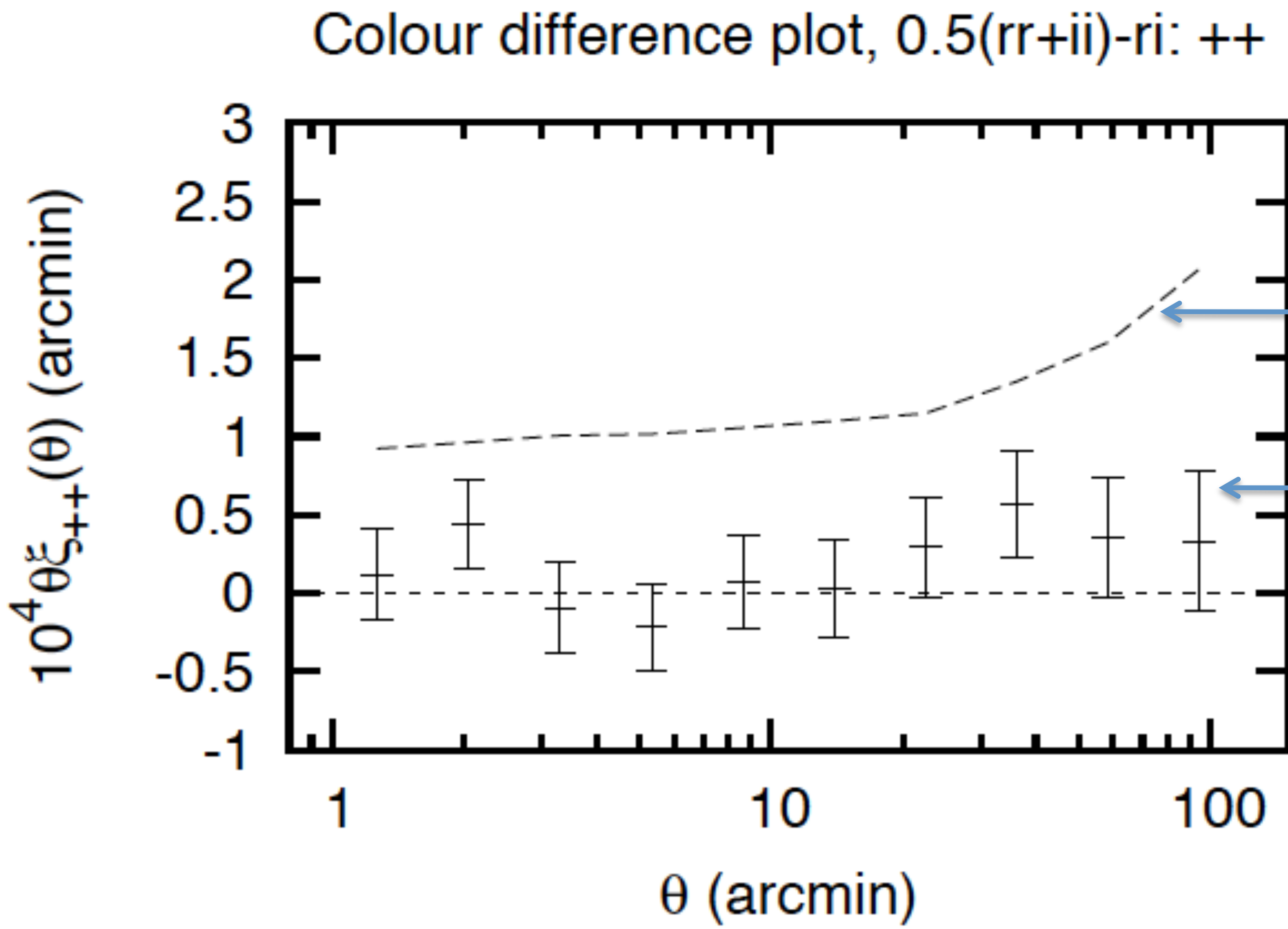
Colors

- Color dependence of PSF is a major issue since it causes stars and galaxies to have *different* PSF!
  - Calibration biases up to several %.
  - Complex z dependence.
  - Airy worse than Gaussian.
- Optical & NIR/WFIRST have different issues:
  - With ≥2 filters, can always correct for broadband slope.
  - Difficult source of color dependence is different – **Balmer/4000Å break** vs emission lines, **Hα+[N II]**.
  - **Need multiple survey filters as a check on any correction scheme.**
  - ≥4 filters (optical + WFIRST-J, H, K) enable us to "dodge" particularly nasty features.



Example of a Null Test – SDSS

In a survey observed multiple times, can search for differences between the shear signals measured in 2 passes. This was needed to convince me that we were doing something right.



Huff et al. (2011)

Statistical error on shear correlation function

Difference between the auto-correlations (rr,ii) and cross-correlations (ri)

Conclusions

- WFIRST represents a unique opportunity to mitigate the major systematics in weak lensing.
  - This was true for DRM1/2, similar strategies should be implemented if we go with the 2.4 m telescope.

- I am excited about the opportunities for my 2nd term on the WFIRST SDT and am looking forward to cooperating with the agency and the Congress to accomplish this project successfully.